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14. ABSTRACT

This paper reports on Moog's efforts to support the design, development, assembly and test of an electric propulsion xenon feed system for a flight technology demonstration program. Major accomplishments include: 1) Utilization of the Moog Proportional Flow Control Valve (PFCV), for the purpose of propellant isolation, pressure, and flow control. With pressure transducer feedback, the PFCV has successfully fed xenon to a 200 watt Hall Effect Thruster in a Technology Demonstration Program. The feed system has demonstrated throttling of xenon, from a very high inlet pressure of 2200 psia, through single stage modulation, to low, absolute pressures of 2.5 to 5.5 psia, accurately controlling them to within ± 0.025 psia with the PFCV. 2) Integration, and manifolding of an entire flight Propulsion System pneumatic circuit. 3) Charging of a flight Propulsion System with certified clean xenon gas for flight application.

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XENON FEED SYSTEM PROGRESS

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This paper reports on Moog's efforts to support the design, development, assembly and test of an electric propulsion xenon feed system for a flight technology demonstration program. Major accomplishments include: 1) Utilization of the Moog Proportional Flow Control Valve (PFCV), for the purpose of propellant isolation, pressure, and flow control. With pressure transducer feedback, the PFCV has successfully fed xenon to a 200 watt Hall Effect Thruster. The feed system has demonstrated throttling of xenon, from a very high inlet pressure of 2200 psia, through single stage modulation, to low, absolute pressures of 2.5 to 5.5 psia, accurately controlling them to within ± <1% with the PFCV. 2) Integration, and manifolding of an entire flight Propulsion System pneumatic circuit. 3) Charging of a flight Propulsion System with certified clean xenon gas for flight application.

I. Xenon Feed System Background

THE desire to minimize components, and combine as many system functions into a component as possible, was the Technology Demonstration Program theme, and an important driver in the definition of the Moog xenon feed system configuration. The program, in addition, had intentions of flying new technology. Also included were Moog's goal of demonstrating, for the first time, active pressure and flow control, in a flight xenon feed system.

The Moog active pressure and flow control xenon feed system steps outside of traditional pressure and flow control feed systems. Traditional pressure and flow control normally relied on a mechanical pressure regulator or "bang-bang" solenoid valves feeding fixed flow control orifices downstream. Regulators carry an associated weight, and required a separate shut-off device to isolate pressure from downstream when it was not demanded. Mechanical regulators normally provide only fixed pressure and flow control; adjustability is very difficult to incorporate, and is weight inefficient. Additionally, mechanical regulators can conveniently provide controlled pressure only greater than sea level.

"Bang-bang" solenoid valves do not provide a small-enough pressure regulation band to satisfy the thruster. The "bang-bang" configuration is also subject to a very high number of cycles.

In this program, Moog has utilized its Proportional Flow Control Valve (PFCV), to throttle high inlet pressures to sub-atmospheric levels and control them to very tight tolerances. Concurrent with pressure regulation, the PFCV has the capability of flow isolation. The PFCV accomplished pressure regulation, integrated with a proportional/integral controller, and a downstream pressure transducer, closing the loop. The controlled pressure would again feed fixed flow control orifices, but would also be capable of changing pressure, and hence, flow. With the capability of controlling pressure below atmospheric levels, control orifice sizes could be maximized and ullage masses could be reduced significantly.

The program presented Moog the opportunity to demonstrate the following feed system advances:
- Make the PFCV the sole pressure management and isolation device.
- Introduce, and demonstrate new low-weight/low fluid volume, pressure transducer.
- Make downstream pressure and volume as small as possible, so that dribble masses would be kept low.
- Make the feed system as responsive as possible, to optimize and extend the capability of the propulsion system.

These goals were fulfilled in this program.

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II. Xenon Feed System Description

A. Introduction

This Moog Xenon Feed System (XFS) was designed to integrate into the primary propulsion system of a technology demonstration mission. The primary propulsion is a 200W Hall Effect Thruster (HET), composed of a thruster (anode) and cathode, along with all of the associated power processing, control, and spacecraft interfacing electronics.

B. System Layout

The XFS schematic is shown in Figure 1. A customer supplied reservoir stores the xenon propellant. It is charged via a Moog Fill and Drain Valve. Downstream of the reservoir is a customer supplied high-pressure inlet transducer, P_{high}, followed by the PFCV. The PFCV is normally closed during non-operation of the system, and serves as the reservoir isolation valve. Downstream of the PFCV is a precision, low-pressure transducer, P_{low}, which provides feedback to a Proportional/Integral controller (PI).

The controller modulates current to the PFCV to provide a desired set point pressure, over the range of inlet pressures. The regulated downstream pressure manifold ultimately feeds two flow control orifices. These two orifices respectively feed the anode and cathode of the HET. The manifold is maintained at a constant pressure, well below atmospheric, to insure a steady flow to the HET.

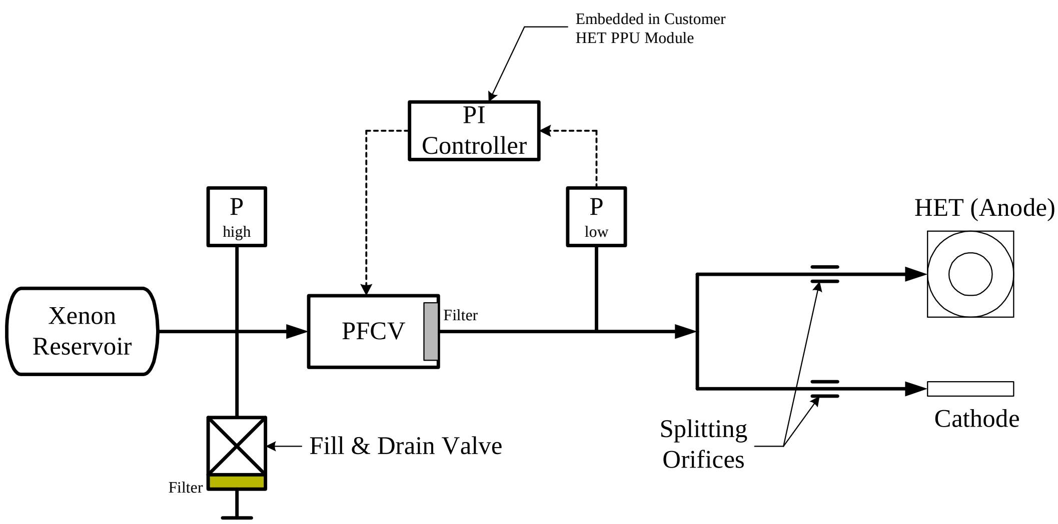


Figure 1.0. Xenon Feed System Schematic

C. Performance Summary

The XFS meets or exceeds the following performance requirements:

Inlet Pressure Range: 2200 to 100 psia
Outlet Pressure Range: 5.25 psia ± <1%

Flow Rate:
- Anode: 0.882 mg/sec
- Cathode: 0.071 mg/sec

Flow Response: < 5 sec.

System components are connected via 1/8 inch stainless steel feed lines and mounted on a customer supplied panel.

D. Moog Supplied System Components

Fill & Drain Valve:

The Fill & Drain Valve has a metal-to-metal seat design and is capable of sealing at low and high pressure. It features an anti-rotation mechanism, which allows opening and closing of the main sealing element without the use of a second tool.

PFCV:

The Proportional Flow Control Valve is a proportional solenoid valve, spring-loaded to be normally closed when unpowered. It features a non-sliding-fit, suspended armature, guided by S-springs. It has a Vespel poppet which seals on a metal orifice pad. This configuration is used on other Moog solenoid valves and regulators. Additional information regarding this valve is detailed in previous papers (1, 2, 3)

Low Pressure Transducer:

The Low Pressure Transducer is a low mass/low volume configuration. It is fully analog and has a range of 0 to 15 psia, to maximize the magnitude of the feedback pressure signal to the PI controller. Moog assisted in the design and qualification of the transducer.

Flow Control Orifices:

There are two flow split orifices in the controlled pressure manifold downstream of the PFCV. Each orifice is made by precision laser drilling orifice holes through a thin membrane, which is part of the orifice housing. As part of the drilling process, the orifice hole is flow checked and adjusted accordingly.

III. XFS Development Program

At the onset of defining a robust feed system, Moog performed a study on different flow control schemes consistent with the operation and characteristics of the PFCV. It was found that closing the loop on pressure in a small volume, bounded by flow control orifices, just downstream of the valve, provided the best feedback scheme. A 3.0 msec response flow meter, and engine current alone, were tried, but generated too much lag in the feedback loop to provide stable and responsive flow control. Moog built a breadboard xenon feed system consisting of a PFCV, a 0 to 25 psia industrial pressure transducer and a Moog industrial PID controller. The feed system was integrated with a thruster, and provided stable flow control. Transient start-ups were smooth. This breadboard system served as a proof-of-concept for the flow control scheme.

The program moved into the engineering model phase. Moog built xenon feed system EM1, which consisted of a PFCV, a 0 to 100 psia digitally compensated feedback transducer, customer provided breadboard PI controller, defined by Moog, and a Fill & Drain Valve. It was first tested as a standalone system, then with the thruster. Flow control was stable and transient start-ups were smooth. However, the feed system displayed an interaction phenomenon with the thruster, which required set point manipulation to provide the correct pressure and flow control level. Additionally, the system would not function when connected to the flight return voltage scheme (introduced at this time), which contained voltage spikes from other equipment.

Following full system testing of the EM1 feed system, the team reviewed the test results and decided on what design improvements should be made. Theses improvements would be incorporated into the EM2 feed system. There were two basic changes that were made to the EM1 xenon feed system. One was to go to a lower pressure range, analog feedback transducer, 0 to 15 psia, in lieu of the digital configuration. It was felt that the digital configuration would be less robust for flight conditions. The regulated pressure set point was raised from 2.5 to 5.0

psia. This, and the 0 to 15 psia pressure range, would raise the signal-to-noise ratio and increase system robustness in an inherently challenging noise environment. The new, low pressure transducer also featured increased EMI shielding and noise reduction improvements. Moog was heavily involved in these improvements.

The EM1 feed system was re-configured into the EM2, with the new low pressure transducer. Performance was excellent throughout the entire inlet pressure range. Flow was stable and transients were smooth. Next, the feed system was integrated with just the thruster, a representative ground version of the propulsion system Power Processing Unit (PPU), and the breadboard PI controller. The feed system performed well feeding the thruster. The feed system also functioned well with the propulsion system return voltage scheme. Flow was stable and transients were smooth, as shown in Figure 2.0. However, there was still a subtle interaction with the thruster. At this time, more extensive tests were run with the thruster. From these tests it was concluded that the low pressure transducer signal was bleeding through the thruster plasma and to ground. To eliminate this condition, Moog isolated the transducer signal leads from exposure to the flow media with a conformal coat.

The feed system was then integrated with the remainder of the propulsion system, consisting of the PPU, interface and control electronics, and feed system PI controller. This EM2 propulsion system became the technical baseline for the flight Propulsion System. The EM2 propulsion system test series verified what the interaction mechanism was between the thruster and the feed system. Interaction occurred when the transducer signal leads were exposed to plasma. Interaction stopped when the leads were isolated from the plasma. The feed system performed well; flow was stable and transients were smooth as shown in Figure 3.0.

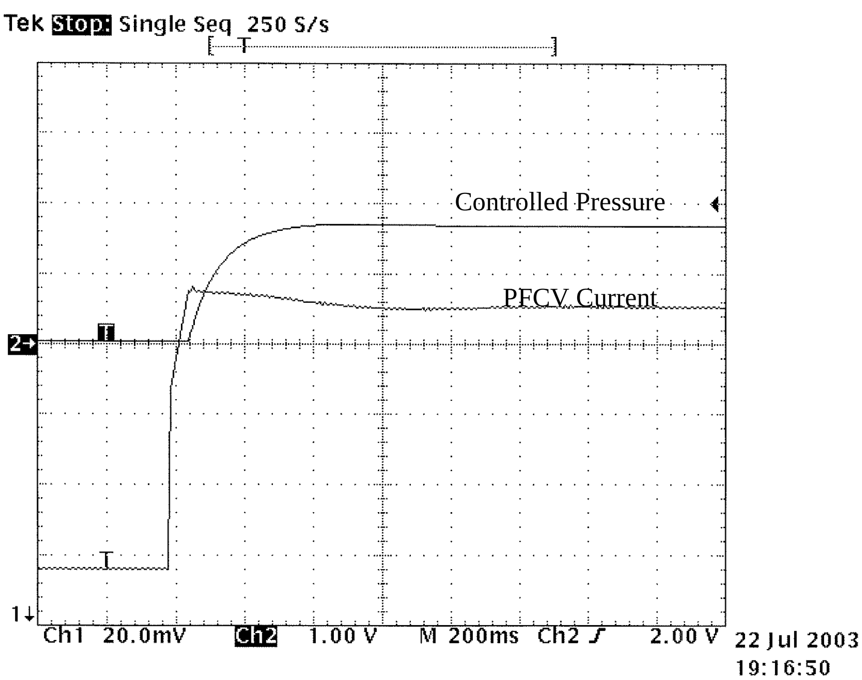
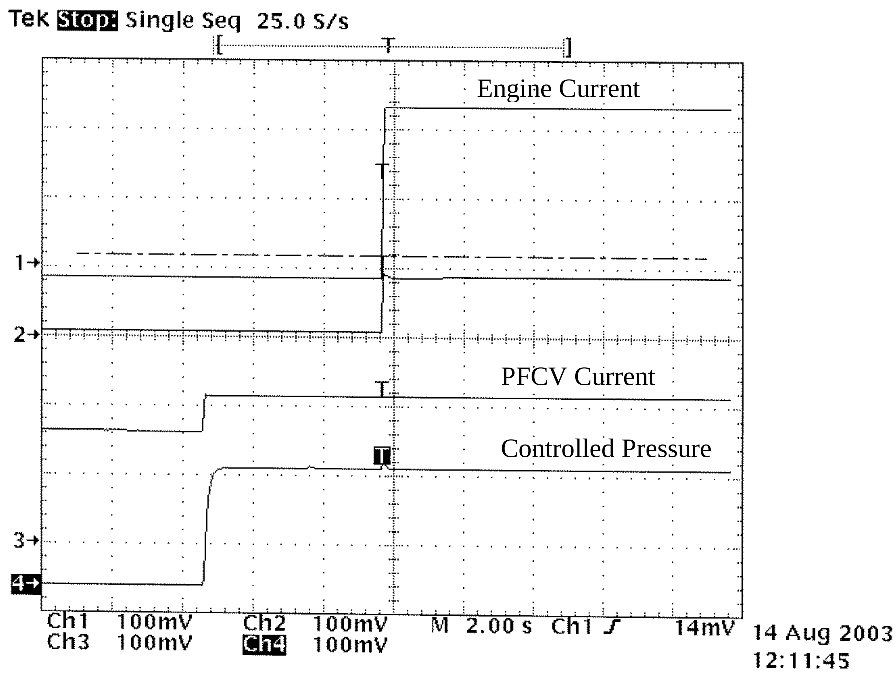


Figure 2.0. EM2 Xenon Feed System Response/Steady State with Xenon at 2176 psia Inlet, Feeding HET (alone)



Tek00031.bmp – 5 min firing (only waveform at the beginning of firing captured)

CH1: Vds (100V/Div) CH2: Ids (1A/Div) CH3: PFCV(I) (50mA/Div) CH4: Line Pressure (1V/Div)

Figure 3.0: EM2 Xenon Feed System Response/Steady State with Xenon, Feeding HET with PPU Electronics

IV. XFS Flight Program

The flight program basically took all of the improvements implemented in the EM2 program and materialized them into flight-worthy components. For the feed system, Moog was also contracted for assembly of the entire pneumatic circuit of the propulsion system. This included all components and feed lines from the Fill & Drain Valve to the Hall Effect Thruster. Pneumatic circuit components included: customer supplied high pressure, inlet transducer and xenon reservoir; propulsion team vendor supplied propulsion panel and thruster-cathode-cant bracket assembly; and Moog feed system components: Fill & Drain Valve, PFCV, low pressure feedback transducer, and flow splitting orifices. A Moog vendor supplied the low pressure transducer.

Included with pneumatic circuit integration responsibilities were proof, flow performance and leakage testing of the system. Beyond these, Moog was given further responsibility to purge and charge the feed system with xenon gas, both for propulsion system integration and testing, and for the flight-storable charge on the bus.

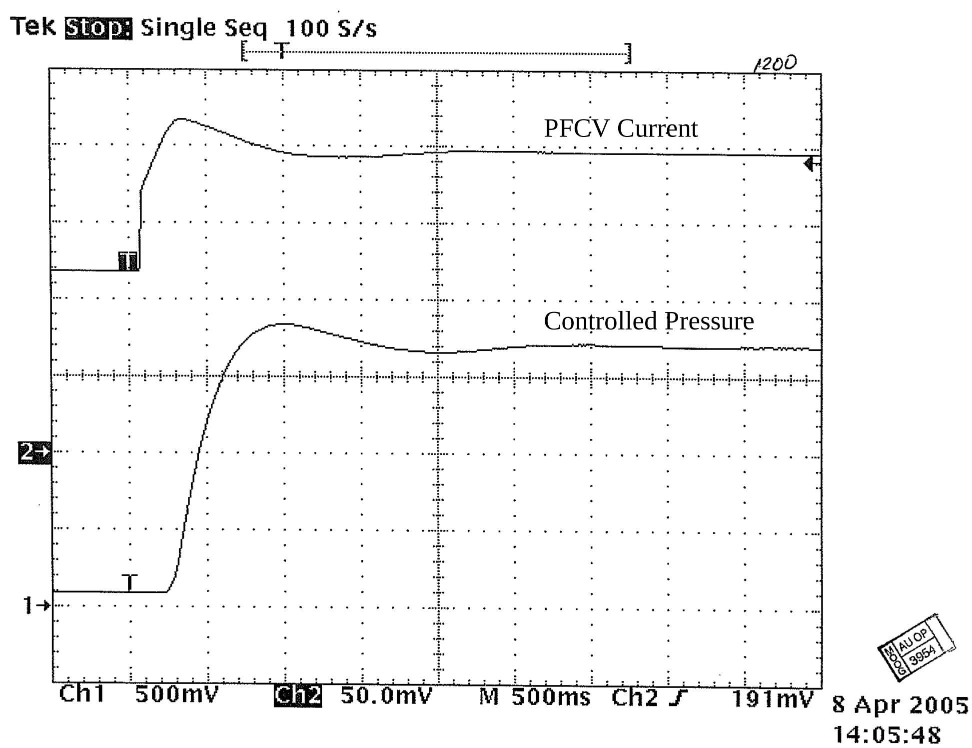
The xenon feed system flight configuration had a few changes from the EM2 baseline. The control pressure was slightly higher, at 5.25 psia. The downstream volume, communicated to the low pressure transducer, between the PFCV and the flow split orifices, was smaller. Therefore, the PI controller gains had to be modified slightly.

Moog proceeded to build and test new flight components and tubing for the flight propulsion system. For the PFCV and Fill & Drain Valve, qualification justification was done largely by similarity to other qualification programs. The only additional qualification requirement, that required more justification beyond qualification by similarity for Moog-produced components, was the PFCV operation during shock and random vibration. Accordingly, the PFCV was tested for leakage while pressurized to maximum inlet pressures, while exposed to random vibration and shock. The PFCV performed per specification.

The qualification of the low pressure transducer was more comprehensive, since it was essentially a new design. Its design varied from other low pressure transducers that the vendor had previously qualified, in that it had a relatively high proof pressure level, to insure that a pressure spike could not affect transducer operation or cause a set point shift. This requirement pushed the design to utilize a thicker diaphragm, with more careful sensor installation and adjustment. There were other requirements that drove the transducer to be different from heritage low pressure designs, and required qualification demonstration. One was the relatively high feed system shock level, which had not been previously demonstrated on any part of the transducer design. Another was the radiation requirement, which drove the transducer electronics assembly to have radiation capable components. This difference required full qualification demonstration.

To make sure the transducer would be feasible for flight shock, Moog exposed the EM2 low pressure transducer to specification shock levels. In the process of shock verification, Moog did a frequency response of the transducer and found it to have no resonances in the specification shock frequency range. Because of its low moving mass, only very light loads were generated on the diaphragm. Because EM2 transducer sensor and housing was identical to the flight configuration, shock qualification for this portion of the transducer was done by similarity. A life cycle test was also done on this transducer, and again served as qualification by similarity for the housing and sensor. A separate flight electronics was cycle and shock tested on its own, and served as qualification by similarity for the electronics. A new unit was used to demonstrate qualification for all other specification requirements, mainly demonstrating operation at temperature extremes and temperature cycling. This unit was placed under protoflight levels for vibration, and is serving as a backup to the flight transducer. The various demonstration specimens combined to become a comprehensive, low pressure transducer qualification.

The Moog flight xenon feed system was mocked-up and performance tested before integration with the thruster, reservoir, high pressure inlet transducer and Fill & Drain Valve. After the PI controller compensation adjustment and verification of stable flow, smooth transient operation and splitting orifice function, the entire propulsion system pneumatic circuit was integrated. All pneumatic circuit components were mounted on the propulsion panel. Feed lines were connected via orbital welding. All weld joints were visually inspected and x-rayed. Just before the thruster and cathode were welded, a final performance verification check was run on the feed system. The system was tested at flight xenon inlet gas densities. Figure 4.0 shows a typical response of the system at an inlet pressure of 1200 psia.



4.0. Flight Xenon Feed System Response/Steady State with Xenon at 1200 psia With Breadboard PI Controller

Upon completion of building and testing of the propulsion system pneumatic circuit on the propulsion panel (see Figure 5.0), the entire subsystem was shipped to the customer for integration of the power processing, interface and control electronics on the propulsion panel. Moog then traveled to the customer test facility for full propulsion system acceptance testing. In addition to propulsion system testing, Moog went through a feed system xenon charging rehearsal. The system was charged with certified xenon gas. Based on stable feed system and thruster performance, the filling rehearsal was deemed successful. Overall, propulsion system testing took only a couple of days, with no major anomalies or concerns developing. For this testing, only telemetry data was available. However, all xenon feed system parameters met expectations: valve current, pressure signal, HET discharge current. The feed system gave all the indications of being solid; shown in Figure 6.0. The thruster and the Propulsion System power processing, interface and control electronics, and mission diagnostic instruments performed well. There was no evidence of any thruster/feed system interaction.

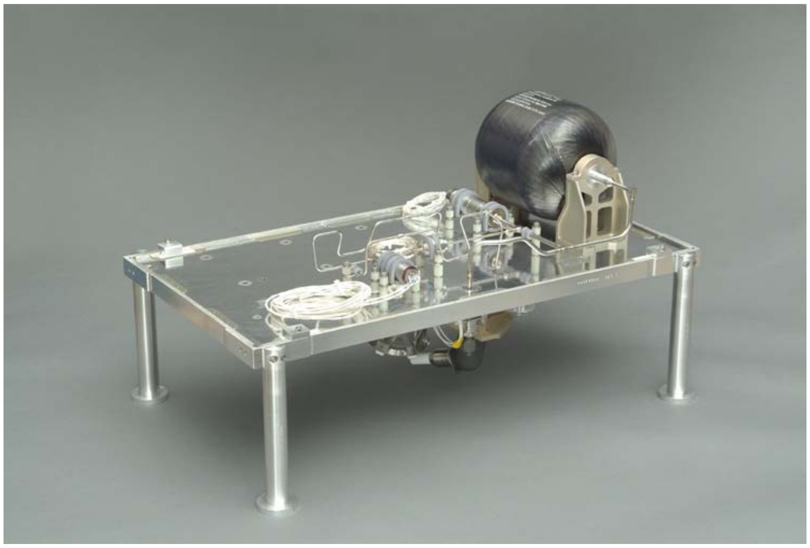


Figure 5.0. Flight Propulsion System Pneumatic Circuit

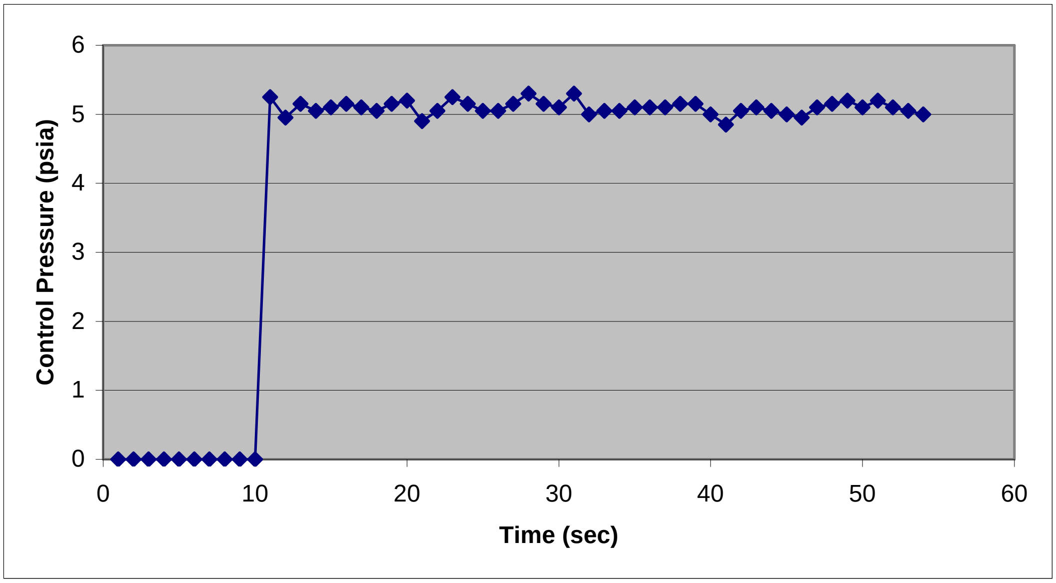


Figure 6.0. Flight Xenon Feed System Response/Steady State with Xenon at 1000 psia in Flight Propulsion System (alone) - Telemetry Data

Following these acceptance tests, the xenon reservoir pressure was reduced to a safe blanket level. The propulsion system was sent to the bus integration site. The feed system was successfully verified. Subsequently, the system was integrated into the bus.

At the appropriate time in the bus schedule, Moog traveled to the bus integration site to perform a xenon fill on the feed system for flight. The Moog filling system, as shown in Figure 7.0, consisted of a purge, evacuation and fill manifold, which connected to the Moog Fill & Drain Valve. Ported to the manifold were a fine calibration high-pressure transducer, a turbo-vacuum pump and ion gauge. Within the manifold were a molecular sieve and isolation and metering valves. A certified xenon gas bottle attached to inlet port. Spent gas bottles were swapped with fresh ones.

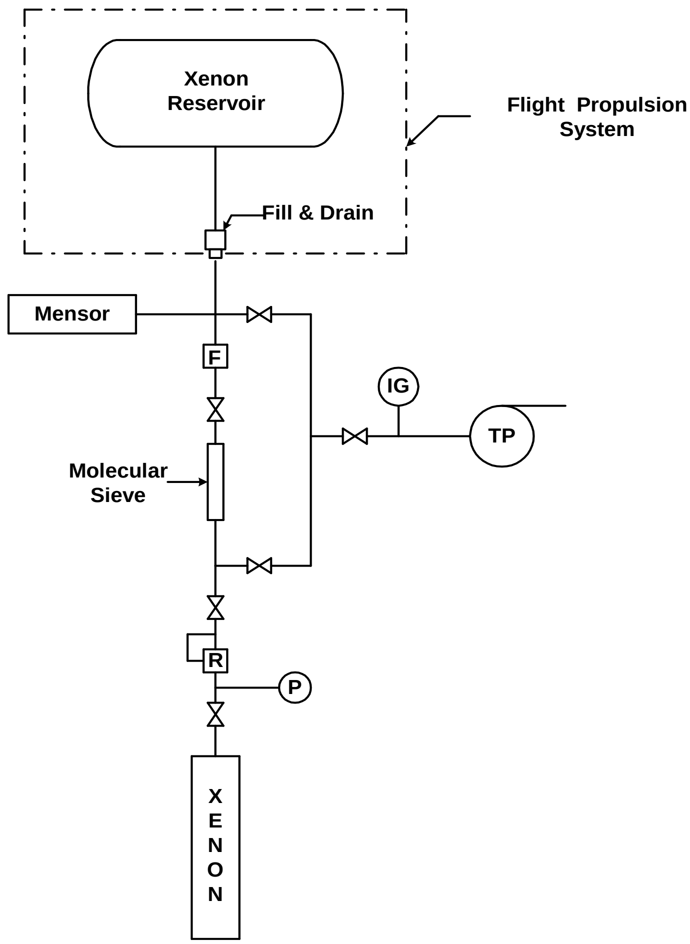


Figure 7.0. Moog Filling System Schematic

The system was assembled and checked for vacuum and pressure leaks. Then, the Fill & Drain Valve was opened, and the still-in-tact blanket pressure was bled off. The high-pressure circuit of the feed system, plus the entire filling system, was pumped down to very low absolute pressures, to insure that the certified clean xenon would fill into a pure system. This very low absolute pressure was maintained for a substantial number of hours to insure stability and purity, and that the system was leak tight.

After purity/leak tightness was demonstrated, the feed system was charged. Moog had to use multiple certified xenon gas bottles to achieve full loading. The process took two days. The reservoir steady state heat sink temperature was slightly higher than room temperature; therefore, steady state reservoir temperature had to be tracked to it. Moog generated a xenon pressure vs. temperature lookup chart of the targeted xenon density required for the mission. This was used to determine that the desired amount of xenon was loaded into the reservoir. A cross check of weight had been made throughout the filling process; therefore there was correlation with temperature and pressure. The Fill & Drain Valve was closed and capped, and was checked for leaks. The manifold was disconnected from the Fill & Drain Valve.

Because of temperature transients in the reservoir from the filling process, and because the reservoir heat sink base was different from room temperature, Moog waited for the system to reach thermal stability after concluding the fill process. The system was deemed tight and filled, based on the inlet pressure transducer telemetry data and final temperature vs. pressure point with respect to the fill curve. The temperature vs. pressure has been monitored consistently since the filling process.

Shortly following the filling process, the bus underwent thermal vacuum testing. In this test campaign, propulsion system performance and other payload verification tests were performed. The thruster, power processing, interface and control electronics, and the xenon feed system performed solidly. All other bus payloads and interfaces performed well. Again, only telemetry data would be available. Flight propulsion system hardware and xenon filling were verified. The solid performance of the feed system and the thruster insured that xenon charge was pure and worthy for flight.

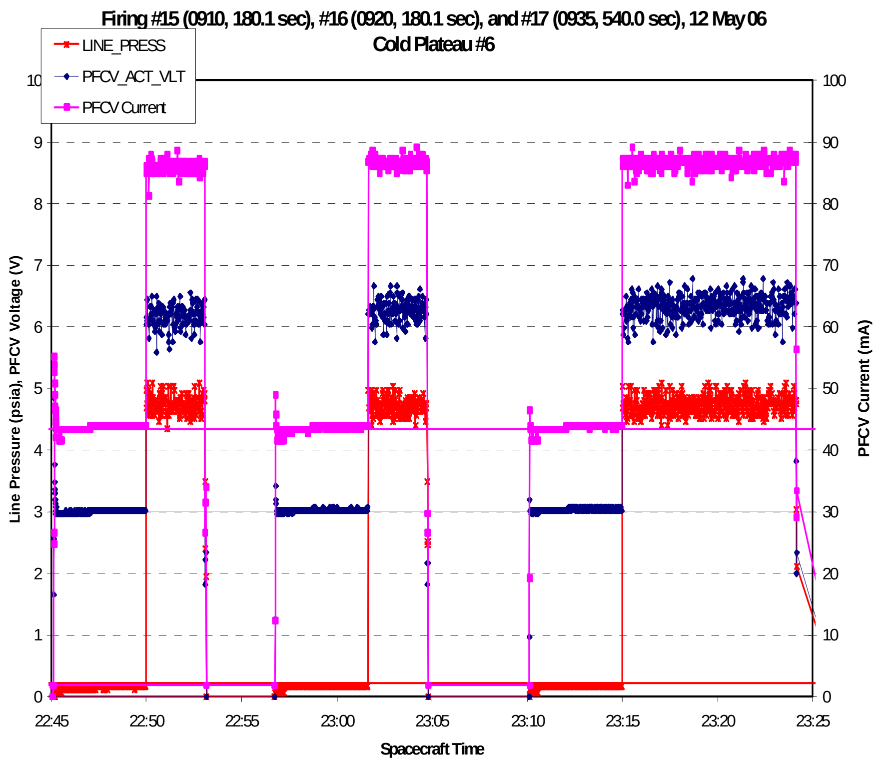


Figure 8.0: Flight Xenon Feed System Response/Steady State with Xenon at 1050 psia In Flight Propulsion System Integrated into Bus - Telemetry Data

A. NEXT STEPS

The next step for the Propulsion System and the Moog xenon feed system is execution of the mission: launch, bus deployment and utilization. This is expected to happen within the next year.

200 W Hall Thruster Development Program: Test Summary					
Test Description	Purpose of Test	Flow Rate/Media	Controlled Pressure	Response: Command to Full Flow (sec)	
				100 psia Inlet Pressure	Maximum Inlet Pressure
Breadboard XFS with Moog PID Controller	Proof of concept – PFCV with pressure feedback	0.596 mg/sec Ar (total)	2.5 ± 0.025 psia	<2	<2 P_{inlet} = 2200 psia
Breadboard XFS with Moog PID Controller – feeding HET	Breadboard XFS feeding Operational HET	Anode: 1.0 mg/sec Xe Cathode: 0.08 mg/sec Xe	2.5 ± 0.025 psia	<2	<2 P_{inlet} = 2200 psia
Breadboard XFS with customer-provided Breadboard PI Controller	Prove-out customer-provided PI Controller	Anode: 1.0 mg/sec Xe Cathode: 0.08 mg/sec Xe	2.5 ± 0.025 psia	<4	<4 P_{inlet} = 2200 psia
EM1 XFS with customer-provided Breadboard PI Controller	Prove-out EM1 XFS before integrating it with the HET	Anode: 1.0 mg/sec Xe Cathode: 0.08 mg/sec Xe	2.25 ± 0.025 psia	<4	<4 P_{inlet} = 2200 psia
EM1 XFS with customer-provided Breadboard PI Controller – feeding HET	Prove-out EM1 XFS feeding HET	Anode: 1.0 mg/sec Xe Cathode: 0.08 mg/sec Xe	2.00 to 2.25 ± 0.025 psia	<4	<4 P_{inlet} = 2200 psia
EM2 XFS with customer-provided Breadboard PI Controller	Prove-out EM2 XFS improvements before integrating it with the HET	Anode: 0.84 mg/sec Xe Cathode: 0.0683 mg/sec Xe	5.00 psia ± <1%	<1	<1 P_{inlet} = 2200 psia
EM2 XFS with customer-provided Breadboard PI Controller – feeding HET (alone)	Prove-out EM2 XFS feeding HET before integrating it with PPU electronics	Anode: 0.84 mg/sec Xe Cathode: 0.0683 mg/sec Xe	5.00 psia ± <1%	<1	<1 P_{inlet} = 2200 psia
EM2 XFS with customer-provided Breadboard PI Controller – feeding HET in all-up Propulsion System	Prove-out EM2 XFS feeding HET after integrating it with PPU electronics using breadboard PI controller	Anode: 0.84 mg/sec Xe Cathode: 0.0683 mg/sec Xe	5.00 psia ± <1%	<1	<1 P_{inlet} = 2200 psia
EM2 XFS with PI controller embedded in PPU electronics– feeding HET in all-up Propulsion System	Prove-out EM2 XFS feeding HET in all-up propulsion system	Anode: 0.84 mg/sec Xe Cathode: 0.0683 mg/sec Xe	5.00 psia ± <1%	<1	<1 P_{inlet} = 2200 psia
Flight XFS with customer-provided Breadboard PI Controller	Prove-out Flight XFS before integrating it with the HET in the flight propulsion system	Anode: 0.882 mg/sec Xe Cathode: 0.071 mg/sec Xe	5.25 psia ± <1%	<2.5	<2.5 P_{inlet} = 1700 psia P_{inlet} = 1200 psia (Flight Xenon Density)

200 W Hall Thruster Development Program: Test Summary					
Test Description	Purpose of Test	Flow Rate/Media	Controlled Pressure	Response: Command to Full Flow (sec)	
				100 psia Inlet Pressure	Maximum Inlet Pressure
Flight XFS integrated in Flight Propulsion System, with flight PI controller embedded in flight PPU electronics– feeding HET	Prove-out Flight XFS feeding HET in all-up flight propulsion system, as well as overall flight propulsion system performance at customer facility	Anode: 0.882 mg/sec Xe Cathode: 0.071 mg/sec Xe	5.25 psia ± <1%	<2.5	<2.5 P_{inlet} = 1000 psia (Flight Xenon Density)
Flight XFS integrated in Flight Propulsion System, with flight PI controller embedded in flight PPU electronics– feeding HET integrated on bus	Prove-out Flight XFS feeding HET in all-up flight propulsion system, as well as overall flight propulsion system performance on bus, at bus integration facility	Anode: 0.882 mg/sec Xe Cathode: 0.071 mg/sec Xe	5.25 psia ± <1%	<2.5	<2.5 P_{inlet} = 1090 psia (Flight Xenon Density)

V. Conclusion

Moog has played a key role in a technology demonstration flight program that is on the verge of flying the first active pressure and flow control scheme in electric propulsion using the Moog PFCV. Moog has demonstrated a robust system design, a comprehensive component and system level development and qualification program, and a xenon filling capability on this program. Moog systematically crafted a flow control/pressure feedback scheme, which is stable and responsive, and operates in a very challenging EMI environment. Moog believes that pressure, in a small volume, is an excellent inner loop feedback method, that can stand alone or easily be driven by engine current (as an executive).

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1) Bushway III, Edward D.; Perini, Richard; “Proportional Flow Control Valve (PFVC) for Electric Propulsion Systems”, AIAA 2000-3745, July 2000.

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3) Barbarits, Joseph K.; Bushway III, Edward D.; “Xenon Feed System Development”, AIAA 2003-4879, July 2003.